Millisecond Oscillations During Thermonuclear X-ray Bursts

Michael P. Muno

Hubble Fellow, Department of Physics and Astronomy, University of California, Los Angeles, CA 90095

Abstract. I review the basic phenomenology and theory of the millisecond brightness oscillations observed during thermonuclear X-ray bursts from 13 of ≈ 70 accreting neutron stars in low-mass X-ray binaries. Compelling observations indicate that the oscillations are produced by surface brightness patterns on the rapidly rotating neutron stars. However, it remains to be understood (1) why the brightness patterns producing them persist for up to 15 s during an X-ray burst, whereas the burning should cover the entire surface in less than 1 s, and (2) why the frequencies drift upward by ≈ 5 Hz during the course of the burst. These peculiarities can probably be explained by taking into account the expansion of the surface layers caused by the burning, zonal flows that form due to pressure gradients between the equator and poles, and Rossby-Alfvén modes that are excited in the surface ocean. Further progress toward understanding how burning progresses on the surface of the neutron star can be made with a next-generation X-ray timing mission, which would provide a larger sample of sources with oscillations, detect sideband signals produced by the spectrum of modes that should be excited in the neutron star ocean, and measure harmonic structure in the profiles of the oscillations. These observations would be crucial for measuring the distribution of the rotation rates of neutron stars, the progression of unstable nuclear burning in the accreted ocean, and the curvature of the space-time around the neutron star.

INTRODUCTION

Thermonuclear X-ray bursts are produced when helium on the surface of an accreting neutron star ignites unstably [see 24, for a review]. The accreted material itself is usually hydrogen. The helium is produced because the accreted hydrogen is compressed and heated by the column of material above it, and begins to burn steadily via the CNO cycle. Eventually, the critical temperature and density are reached such that He can burn via a triple-α process. The burning is unstable, and engulfs the entire surface of the neutron star in less than a second. This results in a 10^{38} erg s^{-1} flash of X-rays that out-shines the emission from the accretion flow for tens of seconds. These bursts recur on time scales of hours to days, and so multiple bursts have been observed from the neutron stars in ≈ 65 low-mass X-ray binaries.

The unstable burning is likely to begin in a small region on the neutron star, and so it has long been expected that the resulting hot spot should produce modulations in the burst flux at the spin period of the neutron star. Indeed, "burst oscillations" have now been observed with *RXTE* from 13 neutron star LMXBs (Table 1). There are several reasons to believe that the burst oscillations occur at the spin frequencies of the neutron stars. First, and most importantly, two of these sources are X-ray pulsars, which exhibit periodic modulations in the persistent emission between bursts at the same frequency as the burst oscillations [4, 28]. The frequencies of all of the oscillations are characteristic to each source, and are distributed uniformly between 270 and 620 Hz. Second, once one accounts for a small frequency drift (described below) the burst oscillations are nearly coherent [31, 26]. In one case, the oscillations are observed to be coherent for 10^5 cycles during a carbon superburst [27]. Third, the maximum frequencies of the oscillations are stable to within a few parts in a thousand in bursts separated by several years [30, 26, 9, 16]. Fourth, the oscillations are strongest in the rises of bursts, when the nuclear burning is likely to be confined to small areas on the surfaces of the neutron stars [30]. Finally, in the tails of the bursts, the amplitudes of the oscillations as a function of energy are consistent with those expected from temperature variations of ≈ 0.2 keV across the surface of the neutron star [18]. As signals from the surfaces of neutron stars, these oscillations can be used to study the evolution of the spin frequencies of accreting neutron stars, the spacetime around the star, and how thermonuclear burning proceeds on the stellar surface.

However, the simplest models of inhomogeneous burning fail to explain two aspects of the oscillations, which are illustrated in Figure 1. First, the oscillations persist for up to 15 s during a burst, long after the burning should have engulfed the entire surface of the neutron star. Second, they drift upward in frequency by up to 5 Hz during the course of a burst, which suggests that the brightness pattern moves opposite the sense of the rotation, such that $\omega_{\rm obs} = \Omega_{\rm NS} - \omega_{\rm pattern}(t)$ [25]. Sev-

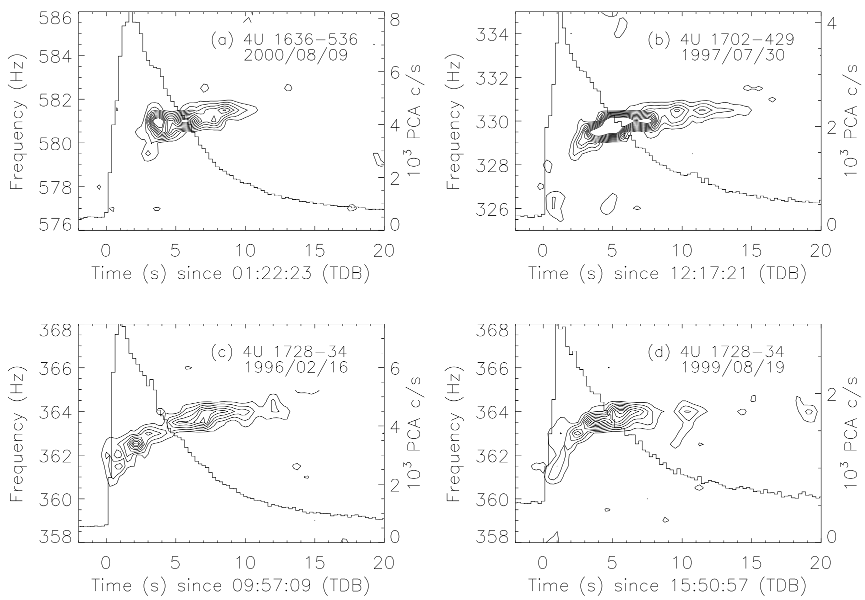

FIGURE 1. Dynamic power spectra illustrating the frequency evolution of burst oscillations. Contours of power as a function of frequency and time were generated from power spectra of 2 s intervals computed every 0.25 s. A Welch function was used to taper the data to reduce sidebands in the power spectrum due to its finite length. The contour levels are at powers of 0.02 in single-trial probability starting at a chance occurrence of 0.02. The PCA count rate is plotted referenced to the right axis.

eral models have been proposed to explain one or both of these aspects of the oscillations.

MODELS OF THE OSCILLATIONS

The upward sense of the frequency drift could be explained by the conservation of angular momentum in an expanding burning layer [25]. Under this model, the energy released in the first second of the burst causes the burning layer to expand and slow relative to the rotation of the neutron star. The frequency drift is observed as the burning layer cools and re-couples to the rest of the neutron star, causing the frequency of the oscillations to increase. Unfortunately, it appears that too little energy is released during a burst to cause the burning layer to expand to the height required to explain the observed frequency drifts [compare 5, 6].

An additional frequency drift could be produced by accounting for the propagation of the cooling front after the fuel has been exhausted [22]. If the burst ignites near the rotational equator, then as the burst cools the pressure at the poles is likely to be larger than at the equator. The pressure gradient and the Coriolis force would then combine to generate a zonal flow opposite the rotation of the neutron star, in the same manner as the trade winds are formed on Earth. As the entire surface cools, the velocity of the flow should slow. Any brightness patterns on the surface would be carried along the zonal flow, again producing oscillations with a frequency lower than that of the neutron star's rotation. Unfortunately, neither of the above models can easily explain the persistence of the oscillations beyond the first second of a burst.

TABLE 1. Sources of Burst Oscillations

Source	$\nu_{\rm burst}$ **(Hz)**	**Ref.**
4U 1608–522	620	—
SAX J1750−2900	600	[11]
MXB 1743–29	589	[25]
4U 1636–536	581	[35]
MXB 1659–298	567	[34]
Aql X-1	549	[36]
KS 1731–260	524	[21]
SAX J1748.9-2901	410	[12]
SAX J1808.4–3658	401	[4]
4U 1728–34	363	[31]
4U 1702-429	329	[26]
XTE J1814–338	314	[28]
4U 1916–053	270	[8]

The unstable nuclear burning that initiates a burst may also excite oscillatory modes in the surface layers of the neutron star [10, 13]. The modes should propagate around the neutron star in the non-rotational frame, with a frequency that depends on the temperature and composition of the surface layers. Although the frequencies of

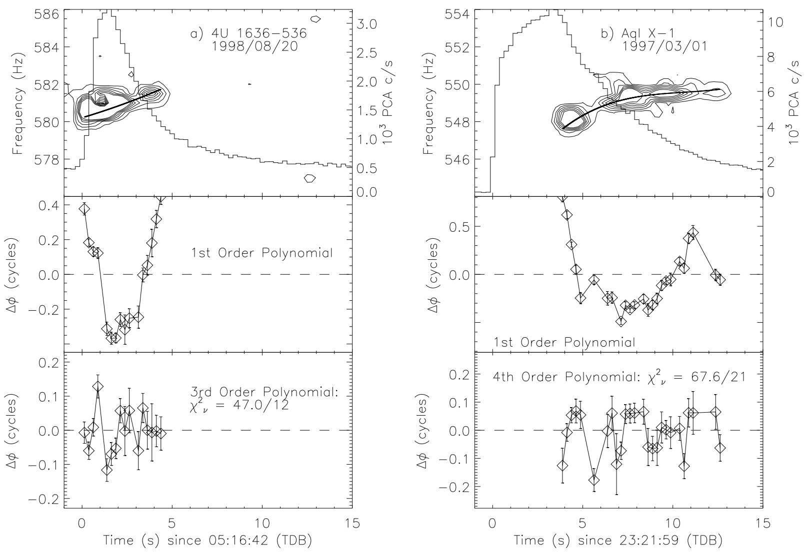

FIGURE 2. Two bursts for which smooth phase evolution models fail to reproduce the observed signals. *Top panel*: Dynamic power spectrum of a burst oscillation, as in Figure 1. The thick solid line illustrates the best-fit frequency evolution. *Middle panel*: The phase residuals assuming the oscillation trains are produced by a signal with constant frequency. *Bottom panel*: The phase residuals assuming that the oscillations evolves according to the models indicated. Sudden 0.1 cycle changes in phase are evident in the residuals.

the most common gravity, Kelvin, and Rossby modes[1] are too large to explain the frequency drifts observed, Fred Lamb has suggested that Rossby-Alfvén modes may have the right frequency. However, in order to explain the burst oscillations, some unknown mechanism must select a single, dominant surface mode, and that mode must always propagate with retrograde motion.

KEY OBSERVATIONS

To better constrain the above models for the burst oscillations, we have carried out a systematic study of them using a phase connection technique commonly used on radio pulsars (Figure 2). To implement this technique, we fold the data in short (0.25 s) intervals about a trial phase model, generally corresponding to a constant frequency, and then measure the phases of each folded profile. We then derive a correction to the initial phase models, by modeling the residuals from the phase model with either a polynomial or saturating exponential using a χ^2 minimization technique. We iterate this process until χ^2 is minimized when comparing the phase residuals to zero. We use the resulting phase models to quantify the coherence of the oscillations [16] and to examine their profiles [17].

If the oscillations are coherent, then a smooth frequency model should be able to predict their phase as a function of time. Although the oscillations appear coherent using this measure in most cases, Figure 2 illustrates two cases in which the best-fit phase model failed to produce a χ^2 that is consistent with zero phase residuals. Out of a sample of 59 oscillation trains, 20% did not appear to evolve smoothly in phase [23, 16]. There are several possible causes of this, including: 0.1 cycle phase jumps that could represent sudden changes in the position of the brightness pattern on the star; 1 Hz s^{-1} frequency shifts that could be caused by sudden changes in the velocity of the brightness pattern; and multiple signals present simultaneously with frequency separations of < 1 Hz that otherwise cannot be resolved with Fourier techniques. This latter possibility is the most interesting, because in at least two instances out of ≈ 100 oscillation trains, multiple signals have been observed simultaneously with frequency separations of ≈ 1 Hz (Figure 3) [16, 14, 8]. Moreover, Deepto Chakrabarty has reported sideband signals 30 Hz below the main burst oscillation in a couple bursts from 4U 1728–34. The simultaneous presence of multiple signals would provide compelling evidence that the oscillations are produced by modes in

[1] Note that these surface modes are present only in the outer ≈ 10 m of the neutron star, in contrast to the global modes that are invoked to limit the rotational frequency of the star by producing gravitational radiation.

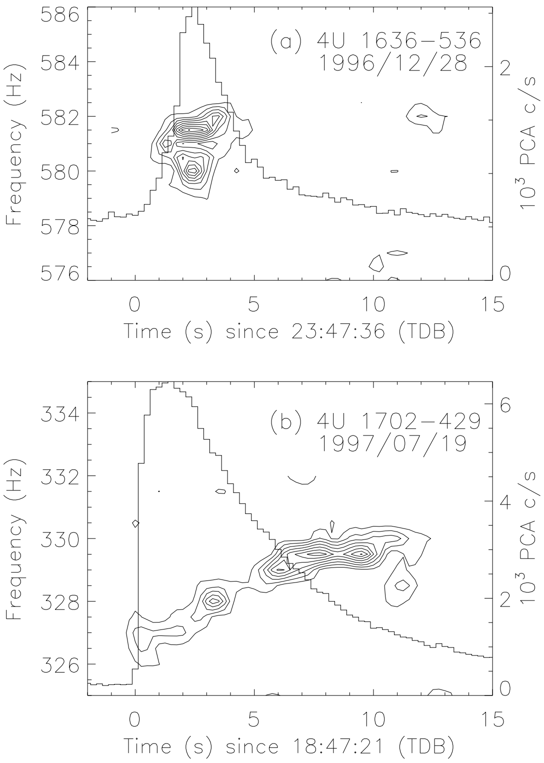

FIGURE 3. Same as Figure 1, for oscillations that exhibited two simultaneous signals separated in frequency by ~ 1 Hz. The secondary signal occurs at 2–3 s in panel a, with a chance probability that it is due to noise of 3×10^{-10}. The second signal at 11 s in panel b has a chance probability of 5×10^{-5}.

the surface with a spectrum of latitudinal and radial wave numbers.

The phase models also allow us to coherently fold the oscillation trains to examine their amplitudes and profiles (Figure 4) [17]. The amplitude of a typical oscillation is 5% rms, and they almost always appear sinusoidal,[2] with upper limits of $< 2\%$ to the amplitudes of harmonic and half-frequency signals. Since the phases of the oscillations are well-measured, we can also coherently summed the profiles from all of the oscillations for each source. For the sources with the largest number of observed oscillation trains, 4U 1728–34 and 4U 1636-536, the summed profiles provide strict upper limits of 0.3% to the amplitude of any harmonic content (Table 2).

We have computed the profiles expected from a bright region on a neutron star, including the expected Doppler

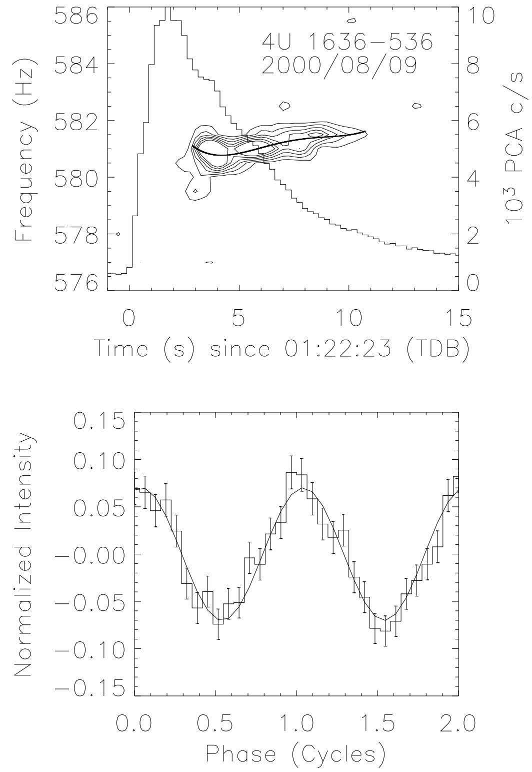

FIGURE 4. *Top panel*: Dynamic power spectrum of a burst oscillation, as in Figure 1. The thick solid line illustrates the best-fit frequency evolution. *Bottom panel*: Profile of the oscillations produced by folding the data about the best-fit phase model. This oscillation train, and all others that we have examined, exhibit no detectable harmonic content.

and General-relativistic light-bending effects, and find that the only plausible ways to explain this lack of harmonic content are if (1) the bright region covers nearly half the neutron star, or (2) a corona of electrons around the neutron star scatters and attenuates the signal from the surface [17]. If the brightness pattern is indeed symmetric, then this suggests that the oscillations could be produced by a mode in the surface layers of the neutron star with azimuthal wave number $m = 1$. However, the scattering hypothesis also merits further study, because energy-dependent scattering could explain the observed lack of the expected Doppler signatures in the phases of the oscillations as a function of energy [7, 18]. The amount of scattering should be determined by simultaneously modeling the burst spectra and the energy dependence of the oscillation amplitudes and phases.

[2] The millisecond pulsar XTE J1814–338 provides the only exception, probably because its relatively strong magnetic field beams the emission along the normal to the surface of the neutron star [28, 1].

TABLE 2. Harmonic Amplitudes of Burst Oscillations. Columns are as follows: (1) Source name. (2) Number of bursts with oscillations used to make a combined profile. (3) Total number of counts in the profile, including background. (4) Estimated background counts in the profile. (5-8) Percent fractional rms amplitudes, or 95% upper limits on amplitudes at n =0.5,1,1.5, and 2 times the main frequency.

(1) Source	(2) No. Osc.	(3) Counts	(4) Background	(5) $A_{1/2}$	(6) A_1	(7) $A_{3/2}$	(8) A_2
4U 1636–536	17*	1.1×10^6	1.3×10^5	<0.6	5.4(3)	<0.5	<0.3
MXB 1659–298	3	2.8×10^4	6.1×10^3	<2.7	9.3(8)	<2.8	<2.7
Aql X-1	3	4.2×10^5	2.0×10^4	<0.6	3.3(1)	<0.5	<0.5
KS 1731–260	4	2.5×10^5	4.5×10^4	<1.2	4.7(2)	<0.9	<0.6
4U 1728–34	24†	1.6×10^6	2.3×10^5	<0.6	5.5(1)	<0.6	<0.3
4U 1702–429	8	6.1×10^5	5.6×10^4	<0.6	4.6(2)	<0.7	<0.7

* 11 oscillations were used to constrain $A_{1/2}$ and $A_{3/2}$, for a total of 9.8×10^5 counts with 1.0×10^5 counts background.
† 13 oscillations were used to constrain $A_{1/2}$ and $A_{3/2}$, for a total of 1.2×10^6 counts with 1.9×10^5 counts background.

THE FUTURE

Observations with *RXTE* have clearly established that the oscillations observed during thermonuclear X-ray bursts occur at the spin periods of the underlying neutron stars, and have provided tantalizing clues as to how nuclear burning proceeds on the surfaces of neutron stars. In the short term, it would be helpful to address outstanding theoretical questions, such as the expected frequencies of Rossby-Alfvén modes, and the amount the oscillation signals are attenuated by scattering as they propagate away from the neutron star. However, a future X-ray timing mission truly is needed to bring these initial observations to their full potential by making several crucial observations.

First, oscillations are currently only observed from 12 of $\approx$ 65 bursting LMXBs, and are only observed from about half of the bursts from any given source. The difference between the amplitudes of the detected oscillations and the upper limits to the non-detections is only a factor of two [19], so a future mission with a larger effective area could greatly increase the number of neutron stars with burst oscillations, and consequently with known spin periods. A larger sample would be important for understanding the distribution of observed spin periods, and thus for exploring why all neutron stars appear to be rotating significantly below their break-up frequency [33, 2].

Second, if the burst oscillations are indeed produced by modes in the surface layers, a future X-ray timing mission should detect a spectrum of signals with different latitudinal and radial wave numbers. The spacing of these modes would allow us to measure the pressure, density, and composition of the burning layers on a neutron star [e.g., 13].

Third, it is likely that more sensitive observations could detect harmonic content in the profiles of the burst oscillations. For instance, a dipolar ($\propto \cos\theta$) temperature distribution on a neutron star should produce oscillations that are slightly-non sinusoidal, because the flux then would be distributed as $\cos^4\theta$ (Figure 5). These harmonics would be just below the detection threshold of *RXTE*, but would be easily detectable with a timing mission with larger area. As is discussed by Tod Strohmayer in these proceedings, the harmonic content of the oscillations is crucial to constraining the compactness of the neutron star, and hence its equation of state [see also 15, 32, 3, 20, 1].

Thus, future observations of millisecond oscillations during thermonuclear X-ray bursts could provide important insight into the physics of neutron stars.

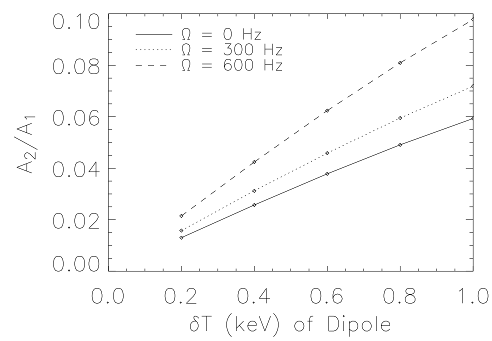

FIGURE 5. Plot of the ratios of the amplitude of the harmonic (A_2) to that of the fundamental signal (A_1) produced by a dipole ($\cos\theta$) temperature distribution of varying temperature contrast δT and neutron star rotation Ω. The amplitudes of the oscillations as a function of energy indicate that $\delta T \approx 0.2$ keV (Muno et al. 2003). The current upper limit on the ratio A_2/A_1 is 0.5%. A future X-ray timing mission with 10 times the effective area could detect harmonics with a factor of 3 lower fractional amplitude.

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